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13. ABSTRACT (Maximum 200 words) Here are some of the highlights in our three year's work supported by this grant: 1) New lessons from a dragonfly flight, namely, designing flapping flight at low Reynolds number need not follow the traditional rule, but instead, could make use of drag as well as lift. 2) Two new Navier-Stokes codes for efficiently simulating multiple wings and ground effects. 3) Experiments of dragonfly flight provided data to our computational models and study the dragonfly's fore-hind wing interactions. 4) Experiments, computation, and theoretical analysis of passive flight of falling paper and plates taught us about models of fluid forces. 5) Comparison of 2D computations against 3D robotic fruitfly experiments allow us to assess the relevance of 2D computations as well as the role of 3D effects in insect hovering. 6) Theoretical analysis of fluid forces including the effect of both the leading and trailing edge vortex sheets, a much needed improvement over the classical theory. 7) Simulations of three-dimensional elastic flapping wings that are actuated by muscle forces, which now finally takes off.					
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COMPUTATION AND MODELING OF INSECT FLIGHT

F49620-01-1-0530

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Theoretical and Applied Mechanics

Cornell University

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August 23, 2005

Objectives

To understand the fundamental physical principles of design and control in flapping flight through the studies of insect flight, and to create a virtual insect on computer.

Status of Effort

Here are some of the highlights in our three year's work supported by this grant:

- 1) New lessons from a dragonfly flight, namely, designing flapping flight at low Reynolds number need not follow the traditional rule, but instead, could make use of drag as well as lift.
- 2) Two new Navier-Stokes codes for efficiently simulating multiple wings and ground effects.
- 3) Experiments of dragonfly flight provided data to our computational models and study the dragonfly's fore-hind wing interactions.
- 4) Experiments, computation, and theoretical analysis of passive flight of falling paper and plates taught us about models of fluid forces.
- 5) Comparison of 2D computations against 3D robotic fruitfly experiments allow us to assess the relevance of 2D computations as well as the role of 3D effects in insect hovering.
- 6) Theoretical analysis of fluid forces including the effect of both the leading and trailing edge vortex sheets, a much needed improvement over the classical theory.
- 7) Simulations of three-dimensional *elastic flapping wings* that are actuated by *muscle forces*, which now finally *takes off*.

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Accomplishments

The Role of Drag in Insect Hovering

Z. J. Wang, J. Exp. Biol., 2004.

Airplanes and helicopters are airborne via aerodynamic lift, not drag. However, it is not *a priori* clear that insects use only lift to fly. A dragonfly uses mostly drag to hover by employing asymmetric up and down strokes along an inclined stroke plane. But is it efficient to use drag? Our computations of a family of strokes, which use various combination of lift and drag to produce the net vertical force, show that using drag can be as efficient as using lift. This finding further leads to an explanation of the anomalously large lift coefficient reported in the literature as well as lead us to construct a simple example in which hovering efficiency can be improved two-fold when using both lift and drag, compared to using lift alone.

2D Comparison vs. Robofly Experiments

Z.J. Wang, J. Birch, and M. Dickinson, J. Exp. Biol. 2004

We compare two dimensional computations against the robotic fruitfly experiments. In particular, we investigate unsteady effects and the degree of agreement between two dimensional computations and three dimensional experiments in several qualitatively different flows. Analysis of the success and failure of a two dimensional model in capturing the forces and flows in three dimensional experiments provides new insight about the role of three dimensional effects in flapping flight, for example, the relevance of the axial flow in dynamic stall.

Computational Method for Solving Unsteady Flows Coupled to Multiple Moving Objects

S. Xu and Z. J. Wang, SIAM J. Sci. Comp., 2005

S. Xu and Z. J. Wang, J. Comp. Phys., submitted,

D. Russell and Z. J. Wang, J. Comp. Phys. 2003.

Blood flow in heart, fish swimming, and bird and insect flight are examples where understanding the coupling between moving boundaries and fluids are essential. A main difficulty in direct numerical simulations of the interaction between a moving boundary and fluids is to resolve the moving boundary accurately and their effects on fluids.

We have made substantial progress in formulating and implementing an immersed boundary method, in which the moving surface are represented as singular force in the Navier-Stokes equations. The singular force enters the numerical scheme as jump conditions. Starting from

the principle jump conditions, we derived systematically the jump conditions across the surface for all first-, second- and third-order space derivatives of the velocity and pressure. The jump conditions for time derivatives of the velocity are also derived. With these jump conditions, the immersed interface method is applicable to three-dimensional incompressible flows with local first- or second-order space and time accuracy.

We have further implemented the immersed interface method to incorporate these jump conditions in a 2D and 3D numerical schemes. We tested 2D code extensively and is currently doing the same with the 3D code. In the 2D case, we study the accuracy, efficiency and robustness of our method by simulating Taylor-Couette flow, flow induced by a relaxing balloon, flow past single and multiple cylinders, and flow around a flapping wing. Our results show that: (1) our code has second-order accuracy in the infinity norm for both the velocity and the pressure; (2) the computational cost is dominated by the pressure Poisson solver and thus the addition of an object introduces relatively insignificant cost; (3) the method is equally effective in computing flow subject to boundaries with prescribed force or boundaries with prescribed motion.

Dragonfly Flight: Fore and Hind Wing Interactions

D. Russell, Cornell PhD thesis, 2005

D. Russell and Z. J. Wang, manuscript in preparation.

Dragonflies are one of the most maneuverable insects, and their flight has two distinct features. First their wings beat along an inclined stroke plane and uses aerodynamic drag to support much of its weight (ZJW, JEB 2005). Second the fore-hind wings are driven by separate direct muscles unlike butterflies and many other insects. As a result, dragonflies can modulate the phase delay between fore and hind wing. During hovering, the wing typically beats out of phase, but when take off or in escape, the wing beats close to in phase. We study this experimentally and computationally and explain a possible advantage of counter-stroking in hovering.

Falling Paper: Passive Flapping Flight

A. Andersen, U. Pesavento, and Z. J. Wang, J. Fluid Mech., 2005.

A. Andersen, U. Pesavento, and Z. J. Wang, J. Fluid Mech., 2005.

U. Pesavento and Z. J. Wang, Phys. Rev. Lett. 2004

We study the dynamics of falling paper as a system of passive flapping flight to gain insight about the naturally occurring flapping motions and to deduce models of the fluid dynamic forces on moving objects in fluids.

On the experimental side, we investigate the aerodynamics of freely falling plates in a quasi

two-dimensional flow at Reynolds number of 10^3 , which is typical for a leaf or business card falling in air. We quantify the trajectories experimentally using high speed digital video at sufficient resolution to determine the instantaneous plate accelerations and thus to deduce the instantaneous fluid forces. We compare the measurements with direct numerical solutions of the two-dimensional Navier-Stokes equation.

On the theoretical side, using inviscid theory as a guide, we decompose the fluid forces into contributions due to acceleration, translation, and rotation of the plate. For both fluttering and tumbling we find that the fluid circulation is dominated by a rotational term proportional to the angular velocity of the plate, as opposed to the translational velocity for a glider with fixed angle of attack. We find that the torque on a freely falling plate is small, i.e., the torque is one to two orders of magnitude smaller than the torque on a glider with fixed angle of attack. Based on these results we revise the existing ODE models of freely falling plates.

Analyzing the above ODE model, we find a transition between steady broadside on descent and oscillatory motion via a supercritical Hopf bifurcation in which the broadside on fixed point changes stability, and we observe a period-doubling bifurcation between tumbling with simple periodic motion and tumbling with alternating short and long gliding segments. We show that the transition between fluttering and tumbling is a homoclinic bifurcation which leads to a logarithmic divergence of the period of oscillation at the bifurcation point, which agrees with the experiment and explains the nature of the observed transition between fluttering and tumbling.

Unsteady Forces on an Accelerating Plate and Application to Hovering Insect Flight

D. I. Pullin and Z. J. Wang, *J. Fluid Mech.*, 2004.

The vortical flow seen in simulations of hovering flight suggested a need for better understanding of the separated flow behind a plate, but limited theoretical tools are available. To fill this gap, we study analytically and numerically the aerodynamic forces on a flat plate accelerating from rest at fixed incidence in two-dimensional power-law flow. An inviscid approximation is made in which separation at the two plate edges is modeled by growing spiral vortex sheets, whose evolution is determined by the Birkhoff-Rott equation, and solved with a similarity expansion. This gives a mechanism for dynamic stall based on a combination of unsteady vortex lift and pure added mass; the incidence angle for maximum vortex lift is $\arccos \sqrt{3/8} \approx 52.2^\circ$ independent of the acceleration profile. Circulation on the flat plate makes no direct contribution. Both lift and drag force predictions from unsteady inviscid theory are compared against those obtained from numerical solutions of the two-dimensional unsteady Navier Stokes equations for an ellipse of high aspect ratio, and with predictions of Wagner's classical theory. Estimates for the shed circulation and the size of the start-up vortices are also obtained.

Three Dimensional Flexible Wing Driven by Muscles

Z. J. Wang, S. Childress, N. Cowen, C. Peskin, manuscript in preparation

In collaboration with Steve Childress and Charles Peskin's group at Courant Institute, I have been applying the immersed boundary method, which treats an elastic structure as force points on fluids, to simulate a flapping wing actuated by simple muscles. The first model was a elastic sheet driven by 'muscles' in the plane of the wing, and the second model uses 'muscles' to shear the double elastic plane to achieve the flapping. Recently, we have improved the muscle-driving mechanism and come up with a hinge design using internal driving. This has a couple of advantages over the previous design: 1) simpler: the body is no longer needed in the computation, and 2) more realistic: eliminated the artificial bending of the previous design. The first test is to simulate transitions to forward flight using such a wing. Above a critical Reynolds number, the symmetrically flapping wing can fly forward against the wind. This provides an ideal model for studying the basic physics of flapping flight, as well as a concrete example to test our computations. The wing now flaps beautifully over a range of flapping frequencies and wing sizes, and it finally generates the thrust required for a forward flight.

Annual Review

Z. J. Wang, *Annual Review of Fluid Mechanics*, **37**, 183-210 (2005)

"What force does an insect wing generate?" Finding answers to this enduring question is an essential step toward our understanding of interactions of moving objects with fluids that enable most living species such as insects, birds, and fish to travel efficiently and us to follow similar suit with sails, oars, and airfoils. We give a brief history of research in insect flight and discuss recent findings in unsteady aerodynamics of flapping flight at intermediate range Reynolds numbers ($10 - 10^4$). In particular, we examine the unsteady mechanisms in uniform and accelerated motions, forward and hovering flight, as well as passive flight of free-falling objects.

Personnel Supported

- Z. Jane Wang (P.I.)
- Umberto Pesavento, PhD Physics (2005), Cornell University
- Anders Andersen, 2002-2005, Postdoctoral Fellow
- Sheng Xu, 2003-2006, Postdoctoral Fellow

Publications

1. Z. Jane Wang, 'Dissecting Insect Flight', *Annual Review of Fluid Mechanics*, 37, 183-210 (2005).
2. Sheng Xu and Z. Jane Wang, 'Systematic Derivation of Jump Conditions for the Three-Dimensional Immersed Interface Method', *SIAM Journal of Scientific Computing*, in press.
3. Anders Andersen, Umberto Pesavento, and Z. Jane Wang, 'Unsteady Aerodynamics of Fluttering and Tumbling Plates', *Journal of Fluid Mechanics*, in press.
4. Anders Andersen, Umberto Pesavento, and Z. Jane Wang, 'Analysis of transitions between fluttering, tumbling and steady descent of falling cards', *Journal of Fluid Mechanics*, in press.
5. Z. Jane Wang, 'The Role of Drag in Insect Hovering', *Journal Experimental Biology*, 207, 4147-4155 (2004).
6. Umberto Pasavento and Z. Jane Wang, 'Falling Paper: Navier-Stokes Solutions, The Model of Forces, and the Center of Mass Elevation', *Physical Review Letters*, 93, 14, 144501-04 (2004).
7. D. I. Pullin and Z. Jane Wang, 'Unsteady Forces on an Accelerating Plate and Application to Hovering Insect Flight', *Journal of Fluid Mechanics*, 509, 1-21 (2004).
8. Rustom Bhiladavala and Z. Jane Wang, 'Effect of Fluids on the Q-factors and Resonance Frequency of Oscillating Micron and Nanometer Scale Beam', *Physical Review E*, 69, 036307 (2004).
9. Z. Jane Wang, Jim Birch, and Michael Dickinson, 'Unsteady Forces and Vorticity Field in Hovering Flight: Two Dimensional Computations vs Robotic Wing Experiments', *Journal of Experimental Biology*, 207, 449-460 (2004).
10. David Russell and Z. Jane Wang, 'A Cartesian Grid Method for Modeling Multiple Moving Irregular Objects in 2D Incompressible Viscous Flow', *Journal of Computational Physics*, 191, 177-205 (2003).

Papers Submitted

- Sheng Xu and Z. Jane Wang, An Immersed Interface Method for Simulating the Interaction of a Fluid with Moving Boundaries, submitted to J. Comp. Phys (2005).

Awards and Honors

- Packard Fellowship in Science and Engineering, 2002-2007
- Provost Award for Distinguished Scholarship, Cornell, 2005
- Invited participant, National Academy of Science's 'Frontiers in Science', Irvine, 2004
- Invited participant, National Academy of Science's 'Frontiers in Science', China, 2003
- NSF Distinguished Lecture, Washington DC, 2002